# AN OVERVIEW OF TERRESTRIAL SEQUESTRATION OF CARBON DIOXIDE: THE UNITED STATES DEPARTMENT OF ENERGY'S FOSSIL ENERGY R&D PROGRAM

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**Abstract.** Increasing concentrations of $CO_2$ and other greenhouse gases (GHG) in the Earth's atmosphere have the potential to enhance the natural greenhouse effect, which may result in climatic changes. The main anthropogenic contributors to this increase are fossil fuel combustion, land use conversion, and soil cultivation. It is clear that overcoming the challenge of global climate change will require a combination of approaches, including increased energy efficiency, energy conservation, alternative energy sources, and carbon (C) capture and sequestration. The United States Department of Energy (DOE) is sponsoring the development of new technologies that can provide energy and promote economic prosperity while reducing GHG emissions. One option that can contribute to achieving this goal is the capture and sequestration of $CO_2$ in geologic formations. An alternative approach is C sequestration in terrestrial ecosystsems through natural processes. Enhancing such natural pools (known as natural sequestration) can make a significant contribution to $CO_2$ management strategies with the potential to sequester about 290 Tg C/y in U.S. soils. In addition to soils, there is also a large potential for C sequestration in above and belowground biomass in forest ecosystems.

A major area of interest to DOE's fossil energy program is reclaimed mined lands, of which there may be $0.63 \times 10^6$ ha in the U.S. These areas are essentially devoid of soil C; therefore, they provide an excellent opportunity to sequester C in both soils and vegetation. Measurement of C in these ecosystems requires the development of new technology and protocols that are accurate and economically viable. Field demonstrations are needed to accurately determine C sequestration potential and to demonstrate the ecological and aesthetic benefits in improved soil and water quality, increased biodiversity, and restored ecosystems.

The DOE's research program in natural sequestration highlights fundamental and applied studies, such as the development of measurement, monitoring, and verification technologies and protocols and field tests aimed at developing techniques for maximizing the productivity of hitherto infertile soils and degraded ecosystems.

## 1. Introduction

The projected growth in the use of fossil fuels in this century (EIA, 2003) means a rising concentration of carbon dioxide ($CO_2$) in the atmosphere unless mitigating steps are undertaken. The response endorsed by the U.S. is to develop new

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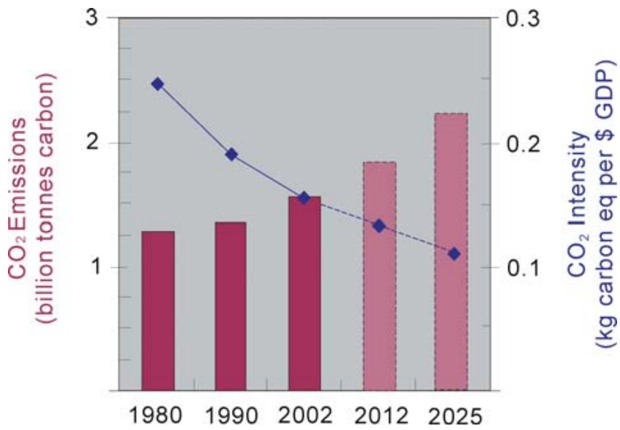


*Figure 1.* $CO_2$ intensity of GDP and $CO_2$ emissions in the United States.

technologies that provide energy and promote economic prosperity while reducing greenhouse gas (GHG) emissions. An appropriate index to gauge progress for such an approach is the GHG intensity of economic activity (kg of $CO_2$ emitted per dollar of Gross Domestic Product). Figure 1 shows that, through normal technological progress, the $CO_2$ intensity of the U.S. economy decreased by 30% between 1980 and 2002 (line in Figure 1). However, strong economic growth overwhelmed these gains, and absolute annual emissions increased by 15% over the same time period (bars in Figure 1) (NETL, 2004). The values for 2012 and 2025 are Energy Information Administration (EIA) estimates based on projected economic activity. To achieve atmospheric stabilization will require average GHG intensity to be reduced at a faster rate than the rate of economic growth.

There are three ways to reduce GHG emissions: (1) achieve the same economic production using less energy through increased efficiency and conservation; (2) utilize carbonless energy sources, such as wind, solar, and nuclear, or reduced C energy sources, such as natural gas; and (3) promote C sequestration. Sequestration entails the capture and storage of $CO_2$ (either as $CO_2$ or as carbon) that would otherwise be emitted to the atmosphere. $CO_2$ can be captured at the point of emission, and the captured gases can be stored in underground reservoirs or converted to mineral carbonates. Alternatively, the $CO_2$ can be absorbed and removed from the air by trees, grasses, microorganisms, and algae at a considerable distance from the source. Ways are also being explored to enhance dissolution of $CO_2$ in oceans; however, this possibility is not yet viable due to uncertainty regarding potential environmental impacts.

The DOE uses an internal planning model, based on cost/supply curves, to evaluate the contribution of various mitigation options to meeting the gap between GHG emissions and the target level, assuming that GHG emissions need to be stabilized at the 2001 level (see Figure 2) (DOE, 2004). The categories "$CO_2$ capture and storage" and "Hydrogen with sequestration" are directly dependent on

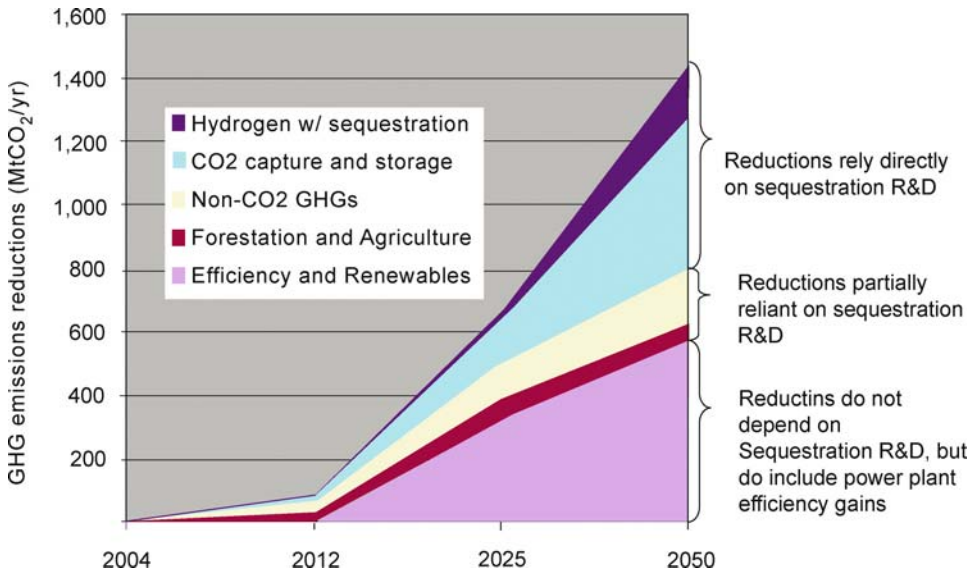


*Figure 2*. Contributions of various technologies to reducing GHG emissions.

research conducted under the DOE Sequestration Program. Together, they account for 45% of the total emissions reduction in 2050. Non-$CO_2$ GHG emissions control and terrestrial ecosystems, which are being pursued by the DOE Sequestration Program in concert with public and private partners, contribute another 12 and 3%, respectively. It is clear that C sequestration can play a pivotal role should GHG stabilization be deemed necessary.

As Figure 2 shows, the requirement for GHG emissions reduction could be very large in the next 20 years or so; and if the potential for sequestration can be realized, the cost of $CO_2$ emissions mitigation can be significantly reduced. In the last five years, sequestration research at DOE's Fossil Energy Department, through the National Energy Technology Laboratory (NETL), has progressed from small-scale, largely conceptual studies to one of the highest priorities in DOE's Research, Development and Demonstration (RD&D) program. The DOE's RD&D program is broad based and includes a wide range of activities and programs. Because it addresses many aspects of GHG mitigation, Core Research and Development (R&D) is one of the most important elements of DOE's program.

## 2. Core R&D

Major areas of investigation included in Core R&D are Separation and Capture of $CO_2$; Direct Geologic Sequestration of $CO_2$; Enhanced Natural Carbon Sinks; Measurement, Monitoring, and Verification (MMV) of Sequestered $CO_2$; Non-$CO_2$ Greenhouse Gases Abatement; and Breakthrough Concepts. The six areas in Core

R&D encompass a broad set of opportunities for the development of technology and the promotion of national and international cooperation through partnerships. Papers discussing the first two areas have been published (Klara and Srivastava, 2002; Klara et al., 2003). The principal objective of this manuscript is to address the third area, enhancing natural pools to increase C uptake in terrestrial ecosystems. The potential for carbon sequestration in the U.S. biosphere is about 600 Tg C/y. If even 50% of this potential can be realized within the next 20 years (by 2025), a meaningful contribution to reducing U.S. $CO_2$ emissions will result. The technical goals of R&D related to enhancing natural sinks are to:

- Assess domestic opportunities in mined land reclamation,
- Complete field testing in representative regional terrestrial ecosystems and determine the effect on these systems,
- Demonstrate the multiple benefits associated with terrestrial sequestration,
- Develop best practice guidelines for possible future deployment, and
- Develop monitoring and verification techniques to ensure the permanence and safety of C sequestration.

Responsibility for terrestrial sequestration research is shared by many Federal agencies, and the terrestrial sequestration program coordinates activities with the DOE Office of Science, the U.S. Department of Agriculture, the Environmental Protection Agency, and the Department of Interior's Office of Surface Mining. The scope of terrestrial sequestration options addressed in the Core R&D Program is limited to the integration of energy production, conversion, and use with land reclamation.

## 3. Terrestrial Sequestration

In the process of photosynthesis, the C from $CO_2$ is biochemically transformed into carbohydrates necessary for plant growth and structure. Most of the C eventually cycles back to the atmosphere through decomposition of the plant material, but a fraction is retained in soils and in wetland sediments.

Through natural sequestration, that is, by increasing the amount of C stored in the terrestrial ecosystem, anthropogenic C emissions can be partially offset. Vegetation and soils are widely recognized as large C storage sinks. The global terrestrial biosphere absorbs roughly 1 Gt net of C annually, an amount equal to about one sixth of all anthropogenic C emissions (IPCC, 2001). The inventory of C stored in global terrestrial ecosystems equals roughly 2,000 years worth of annual net absorption (at current rates), or $2,000 \pm 500$ Gt of C (Houghton et al., 2001).

In the near term, sequestration of C in terrestrial ecosystems offers a low-cost means of reducing net C emissions with significant collateral benefits: restored habitat for plants and wildlife, reduced water runoff, and increased domestic production of agricultural and forest products. Terrestrial C sequestration could serve a strategic role in offsetting C emissions from vehicles and other dispersed energy systems, such as residential heating and small industrial plants. It is estimated (Lal et al., 2003) that, with the right incentives, about 290 Tg C/y for up to 30 years could be stored in U.S. soils.

Reforestation of degraded mined lands offers significant potential for C sequestration. Rates of sequestration depend on several variables, including plant species selection, climate, silvicultural technique, soil quality, etc. Soil C sequestration is relatively slow in the first half (20 years) of a reforestation project with forests sequestering up to 1.9 Mg C/ha/y. Rapid uptake of $CO_2$ occurs during the second half (years 20–40) of a terrestrial sequestration project's life with rates of sequestration ranging from 3 to 4.9 Mg C/ha/y. These results are based on feasibility studies performed to date (Follett et al., 2001). As forests mature, the rate of C sequestration decreases rapidly; the forests senesce and may no longer be active C sinks. However, forest growth can make a significant contribution in the intermediate term while other C management techniques are being developed and implemented. Several papers and reviews pertinent to soil C sequestration in mined lands have appeared recently (Janzen et al., 1997; Paustian et al., 1997; West and Plosst, 2002; Lal, 2004; Post et al., 2004; Bronick and Lal, 2005).

The goal of the terrestrial sequestration R&D program is to integrate C sequestration in vegetation and soils with fossil fuel production and use by rehabilitating mined lands and using waste materials, where possible. This option can provide economic and environmental benefits by offsetting a portion of the nation's $CO_2$ emissions. One option that has been considered is C trading. This would permit landowners who carry out a program to promote C accumulation on their land to amass C credits that could be sold to power plants or other GHG emitters. However, better understanding and monitoring of below ground C balances and processes are essential for soil C quantification, better evaluation of various C sequestration strategies, and for verifying C credits for trading purposes.

The three major research thrusts for terrestrial sequestration are enhancement of $CO_2$ uptake through improved silvicultural practices and soil amendments; increased understanding of ecosystem dynamics; and measurement, monitoring and verification of the amount of C sequestered in soils and in above ground vegetation.

### 3.1. SEQUESTRATION ON MINED LANDS

Much of the surface mining in the Eastern U.S. is on forested lands. After mining, most of these areas are restored as grasslands. Thus, there is a strong need to assess terrestrial C sequestration in forests and other ecosystems. Worldwide, nearly $2 \times 10^9$ ha of lands are degraded to some degree (Oldeman and Vanengelen, 1993) and may be capable of sequestering from 0.8–1.3 Gt C/y (Metting et al., 2001). In the United States alone, $0.63 \times 10^6$ ha of land are classified as disturbed mine lands, mostly land stripped for coal, with a C sequestration potential of 1.3 Mt of C/y (Lal et al., 1998; Lal et al., 2004). Lands associated with other mining activities also have the potential to store an equal amount of C in soils, but studies documenting rates of C sequestration of such lands are lacking (Wullschlegar et al., 2004). Although the potential of mined lands for C sequestration is only a small fraction of the total potential of all soils, this work is still highly significant because it is important to restore the productivity of mined lands and because the techniques developed are applicable to degraded lands in general, not just mined lands.

A number of projects are involved with determining the optimum conditions necessary to reforest surface-mined land. Stephen F. Austin State University (SFASU) is studying the sequestration potential from reforestation of abandoned mined lands using Northern red oak (Huang and Kronrad, 2004; Huang et al., 2004). Within the Appalachian coal region, there may be up to 400,000 ha of abandoned mined lands. These areas contain little or no vegetation, provide little wildlife habitat and little benefit to local ecosystems; they may even have a negative effect, due to acid mine drainage. Reclamation and reforestation of these sites has the potential to sequester large quantities of C in terrestrial ecosystems.

The objectives of the SFASU project are to determine the profitability of forest management in the Appalachian region when only timber is considered and when both timber and C credits are considered; to determine the optimal forest management schedule using the U.S. Forest Service's growth and yield models; and to determine the maximum amount of C that can be sequestered on abandoned mined lands. Results indicate that, depending on the quality of the site and the alternative rate of return, a timber owner could expect net revenue per megagram (tonne) of C stored in the range of a profit of \$35 to a loss of \$10, not including any return from sale of C credits. These results indicate that there will probably need to be an incentive, such as the sale of C credits, to entice landowners to invest in timber production.

Virginia Polytechnic Institute (VPI) is conducting a study of how soil properties influence the amount of C sequestered by comparing mined and unmined forest lands (Burger and Rodrigue, 2003; Rodrigue and Burger, 2004). Researchers analyzed C sequestration rates and amounts for fourteen mined and eight unmined forest sites to develop mine soil classification criteria. This work showed that after 20–55 years, total site C levels in forests on mined land averaged 217 Mg/ha, compared to total C levels of 285 Mg/ha for natural forests. Net C sequestration, i.e., the balance between C input and output through respiration and decomposition along with any hidden C costs of fertilizer and amendments (Robertson et al., 2000), is a function of forest age and site productivity. Based on projections of C sequestration on these sites, successful reclamation and reforestation can restore the potential of forests and forest soil systems to sequester C at pre-mining levels within about seven decades. Carbon sequestration potential was restored on low quality sites, but potential was degraded on medium and high quality sites. Better reclamation techniques are needed to increase the potential of forest and forest soil systems to sequester carbon at pre-mining levels for the entire spectrum of sites. Thus, forests on mined land can be as productive, diverse, and valuable as forests on unmined sites, if mined sites are restored correctly.

The University of Kentucky is conducting a study that may change current mine reclamation perceptions and practices to make loose dumped material and forest establishment the preferred choice as compared to grasslands establishment on compacted soil. Kentucky researchers have found that most tree species survive better and grow faster on uncompacted soil. Project objectives include development of concepts that combine capture and storage of C with a concomitant reduction of criteria pollutant emissions and demonstration and verification of large scale C sequestration by reforestation of mined lands using high value tree species.

Three studies will be conducted on over 200 ha in three distinct mining regions in Southeastern and Western Kentucky. Studies will compare the effect of climate, spoil depth, compaction, and chemical and mineralogical properties on forest establishment and ecosystem processes. Trees selected for this project will consist primarily of those species that will maximize the likelihood of long-term C sequestration. Nitrogen (N) fixing species, such as locust, and conifers and other faster growing, less valuable species will be mixed with hardwoods to provide diversity. After tree planting, the study sites will be monitored for weather, seedling health, biomass production, degree of browsing by wildlife, soil characteristics, moisture content, C flux, value as wildlife habitat, and the quality of water runoff (Barton et al., 2004).

The cost of various practices, including ripping, dumping, grading, and application of spoil modifiers, used in establishing tree cover, will be determined. As the trees grow and mature, the quantity of C accumulated will be evaluated to determine the most efficient system for sequestering C. In addition, benefits associated with a no-harvest scenario, such as recreational use, improved water quality, and improved wildlife habitat, will be included.

The Tennessee Valley Authority (TVA) is conducting a project called the Carbon Capture and Water Emissions Treatment System (CCWESTRS) (Brodie et al., 2005). The objective of this project is to assess the potential for using power plant by-products to improve the fertility of surface-mined land. The test site is 40 ha of low quality mined land adjacent to TVA's Paradise Fossil Plant. The Paradise facility includes both flue gas desulphurization (FGD) units for $SO_2$ control and upstream selective catalytic reduction (SCR) units for NOx control. The by-products from these treatment units are gypsum from the FGD unit and waste water that not only contains certain pollutants resulting from coal combustion, such as As, B, Cu, Cr, Ni, Se, Zn, and other trace elements, but also ammonia that is not consumed in the SCR unit, substances that would normally have to be removed before discharge of the water into a lake or stream. However, using the effluent as irrigation water for plants should add not only needed soil moisture but also N. It is expected that any metals present will not adversely impact tree growth and that aqueous pollutants should be removed through plant uptake and soil adsorption. Furthermore, FGD gypsum is an effective mulch for trees, preventing loss of soil moisture and curbing competition from weeds.

Treatment variables are gypsum mulch depth, irrigation water rate, and tree specie. The FGD wastewater could not be used for irrigation due to its high boron (B) content (70 ppm), which would be phytotoxic to the trees, and due to the higher concentrations of metal pollutants, which were determined to be too risky during these initial years of the project. Therefore, irrigation water with a B content of about 7 ppm and much lower metals concentrations was taken from the fly ash settling pond which receives the FGD wastewater. First year survival rates exceeded 80%. Both tree species reacted favorably to irrigation, but differed significantly with respect to mulch depth. Sycamore was not much affected by mulch depth, but sweet gum survival decreased as mulch depth increased. Potential benefits of the project are development of a passive, high-volume water treatment process, use of power plant waste products to increase C sequestration, and conversion of mined lands to beneficial use, such as wildlife habitat and silviculture. The project is expected to sequester 3.4–6.7 Mg C/ha/y for about 20 years. Preliminary economics indicate that CCWESTRS has the potential to approach or meet the DOE's sequestration cost goal of $40/Mg C sequestered.

The Ohio State University is conducting a project to assess the soil organic carbon (SOC) sequestration potential of reclaimed mined soils in Ohio and the Northern Appalachian region (Shukla and Lal, 2004; Shukla et al., 2004). The project is identifying biophysical processes involved in SOC sequestration in reclaimed mine soils. The study includes six sites reclaimed prior to 1972 without topsoil application and six sites reclaimed after 1972 with topsoil application, equally divided into forest and grass cover. Two unmined control sites were also identified, one under forest and the other under grass cover. Soil samples were collected from all sites and analyzed for bulk density, SOC concentration and stock (amount of C/ha), total N, pH, and electrical conductivity. Conductivity and pH measurements indicate that all sites are suitable for growing grass and trees. Results indicate that mining significantly depletes SOC, as indicated by a comparison of SOC at a site mined in 2003 (1.9 g/kg; 3.5 mg/ha) with an unmined site (12.9 g/kg; 18.7 Mg/ha). The SOC concentrations and stocks at the test sites were strongly correlated with duration since reclamation, which accounted for approximately 75% of the variation in results.

This project is investigating the mechanism of C sequestration in these mined soils, estimating rates of sequestration in different types of soils of Ohio, assessing the potential of different land management practices for the sequestration of C, how these practices affect soil development and water transmission properties, and whether the possibility of trading C credits can stimulate investment in adoption of recommended management practices. Finally, a model that incorporates all the variables listed above will be developed for use in estimating the potential for C sequestration on reclaimed mined soils in Ohio. An optimum suite of land management practices can then be identified to enhance C sequestration on these lands.

### 3.2. MEASUREMENT, MONITORING, AND VERIFICATION

This program element seeks to develop accurate, low cost devices to measure C stored above ground and in the soil in both natural and managed lands. The difference in C storage between a GHG sequestration project's C inventory and the business-as-usual scenario represents the impact that is truly the result of the project rather than simply the result of factors that would have occurred anyway. The business-as-usual scenario, called the baseline, is essentially a future projection based on historical data of what would happen if the sequestration project were not implemented. Cost-effective methods are needed not only to quantify the amount of C storage within a project area, but also to estimate the amount of C storage that would have occurred had the project not been undertaken. For terrestrial carbon sequestration to be accepted as a strategy for reducing GHG emissions, the technical issues involved need to be overcome through good science, sound policy, and technological innovation.

According to the Intergovernmental Panel on Climate Change (IPCC), deforestation accounts for about 20% of annual global emissions of $CO_2$. The IPCC estimates that 12–15% of the fossil fuel $CO_2$ emissions between 1995 and 2050 could be offset through slowing tropical deforestation, allowing these forests to regenerate, and engaging in plantation establishment and other forms of agroforestry (Houghton et al., 1996).

The DOE is working with The Nature Conservancy (TNC) through the Climate Action Project Research Initiative to develop and apply appropriate tools and techniques for cost-effective measurement of terrestrial C sequestration. These techniques are being applied to on-the-ground carbon pilot projects. TNC, with its partner Winrock International, has developed regression equations of tree biomass as a function of tree height combined with either diameter at breast height or crown area. Multi-Spectral 3-Dimensional Aerial Digital Imagery (M3DADI), which collects very high resolution digital imagery from an airplane, can be used to measure tree height, crown area, and vegetation type and display the results on a computer video screen. One of the challenges for C benefit estimation is the lack of data on the C content of heterogeneous landscapes that are intermediate between grasslands and forests. Preliminary results indicate that M3DADI can be used to estimate C inventories in such areas (Brown et al., 2004; Brown et al., 2005). TNC is also studying native forest restoration on abandoned mined lands and lands that were previously mined and reclaimed to unproductive grasslands. A baseline analysis was completed using satellite images to detect rates of land use change.

The importance of the project is its role in validating technology and developing protocols to measure carbon in soils and in above ground vegetation. Although most of the sites being surveyed are in South America, the technology is transferable to other areas and is being tested in the U.S. Feasibility studies on several different

U.S. ecosystems are being conducted to determine for which of these ecosystem types carbon sequestration is a viable option. In addition, soil monitoring is being conducted using the LIBS technique (discussed later) being developed by the Los Alamos National Laboratory (LANL). TNC and LANL are collaborating on the development of a soil sampling plan to measure soil carbon in both tropical and domestic ecosystems. TNC and Geographical Modeling Services have also developed two models (FRCA and GEOMOD) which project future land use changes and resulting changes in carbon storage. The models can be used to establish baselines to compare against projects.

The Los Alamos National Laboratory (LANL) is conducting a project with the objective of developing an integrated suite of technologies to measure, monitor, assess, and manage terrestrial C inventories. Laser-Induced Breakdown Spectroscopy (LIBS) is one promising new measurement technology that could supply the necessary accuracy and precision for measurement of soil C. With LIBS a short laser pulse is fired at the sample to be analyzed. The high temperature of the laser creates a plasma, and as the plasma decays (approximately 1 $\mu$s after the pulse), excited atoms in the plasma emit light, which is picked up by a detector. Each element emits light with a wavelength characteristic of that element, and the intensity of the light is a function of the concentration of the element (Cremer et al., 2001; Ebinger et al., 2003; Cremer, 2004).

Even though the cost of individual soil C analyses is relatively small (Lal et al., 2003), the cost of measuring soil C on a regional scale using conventional sampling methods, including the cost of collecting the samples in the field and transporting them to the laboratory, can be an economic factor in determining changes in soil C. Development of a cost effective, calibrated, portable LIBS instrument for rapid in-field analysis of soil C is highly probable using LANL technology. Prototype LIBS instruments have been built and calibrated, and a person-portable instrument has been fabricated. Monitoring C cycles in soils is another advance that would compliment LIBS measurement technology. Development of soil microbial indicators is a new tool to monitor C cycling and determine the extent of C sequestration. LANL has also been conducting work at mined sites to determine the best post-mining land management practices that would enhance plant growth (Fessenden et al., 2004).

The Brookhaven National Laboratory (BNL) is also developing instrumentation for soil analysis. The differences between the BNL and LANL approaches are substantial, the most significant ones being that the BNL system is non-destructive and samples large soil volumes (tens of liters) *in situ* rather than requiring the extraction of core samples for analysis (Wielopolski et al., 2004a, b). The goals of this project are to develop a system for soil analysis that is safe, rapid, inexpensive, noninvasive, and can be used in stationary or continuous scanning modes. By sampling large volumes, variations in local elemental concentrations due to aggregation and other phenomena are averaged out. Similarly, continuous scanning of large areas provides an estimate of the mean soil elemental concentrations in the field to an approximate depth of 20 cm, depending on soil conditions. Furthermore, in addition to measuring elemental concentrations of soil elements, such as C, nitrogen, potassium, and oxygen, the BNL system can be calibrated to simultaneously measure soil bulk density and moisture. Currently, standard and advanced methods, such as LIBS, are based on point sampling and destructive analyses that require multiple procedures, thus preventing reanalysis of the same site or even the same sample. The number of samples required in these methods is large in order to reduce the error in the average C measurement to an acceptable level.

The BNL measurement method is based on Inelastic Neutron Scattering (INS) of fast neutrons and Prompt Gamma Emission (PGE) following capture of thermal neutrons. Fast neutrons, produced by a pulsed neutron generator, are directed into the soil where they undergo INS with C and other elements. At the same time they slow down (thermalize) through elastic collisions and are captured, stimulating PGE with some of the soil elements. To separate these processes, two gamma ray spectra are acquired simultaneously, an INS spectrum during the neutron pulse and a PGE spectrum acquired between the neutron pulses. The emitted gamma rays are detected using an array of NaI scintillation detectors. The net number of counts in the photopeaks in the measured gamma ray spectra is proportional to the corresponding elemental concentrations in the soil. Following simplified calibration, in which C was homogenously distributed in a sandpit, the feasibility of this approach was demonstrated in double blind studies at three different sites: an oak forest, a pine stand, and a sandy patch area.

The INS processes are so fast that a system towed at speeds of 10–15 km/h moves about a millimeter during and between the neutron pulses, so that it behaves, for all practical purposes, like a stationary system. Such measurements will yield integral counts over the covered area or, alternatively, a true mean value of an elemental concentration per unit area.

### 3.3. OVERCOMING NON-TECHNICAL IMPEDIMENTS TO IMPLEMENTATION

In addition to the technical problems which must be overcome before terrestrial sequestration can be fully practiced, some regulatory and public acceptance issues will have to be resolved, such as spreading waste products from power plants onto reclaimed land.

The Oak Ridge National Laboratory (ORNL) and Pacific Northwest National Laboratory (PNNL) are conducting a project aimed at enhancing C sequestration on marginal lands disturbed by activities such as mining, highway construction, or poor management practices (Palumbo et al., 2004). The team is studying the addition of amendments from industrial processes to soils to increase C uptake and retention. One goal is to identify optimal strategies for selecting and delivering amendments to maximize their contribution to C sequestration. Another goal is to foster interactions between the scientific and user communities to maximize transfer of technology for enhancing terrestrial C sequestration through use of by-products of coal combustion and other industrial processes to enhance the C management of degraded lands.

The approach being used by ORNL and PNNL is to evaluate existing sites, conduct laboratory experiments to identify key amendments and potential management strategies, communicate with involved parties through workshops, design field experiments, and study nontechnical impediments to implementation. Factors to consider in evaluating existing sites include the distribution of soil carbon by depth as a function of treatment, age of site, soil characteristics, and the microbial community present. Soil amendments tested include sawdust, biosolids (manure), fly ash, and flue gas desulfurization (FGD) solids.

Field and laboratory studies of the mechanism of carbon sequestration and the effect of various amendments and treatments on the chemistry are involved. Initial results from these studies (Amonette et al., 2004) show substantial enhancements with alkaline fly ash amendments. These enhancements of alkaline fly ash stem from its ability to increase the soil pH (i.e., a liming effect), and from the adsorption of soil organic carbon precursors on the residual carbon present in the ash. The high-C ash produced by low-$NO_x$ boilers is particularly effective as an amendment for soil carbon sequestration enhancement.

A significant factor being addressed by this project is assessment of the nontechnical barriers to implementation, such as regulations, interactions with landowners, bond requirements, and public perceptions. For example, bond release issues drive mining companies to reclamation approaches that can be completed rapidly (grass grows faster than trees). Also, the desire of regulators to protect stream quality may result in requiring compaction to the extent that trees cannot grow. Any future policies that lead to increased terrestrial C sequestration will require addressing such issues.

## 4. Conclusions

There is a significant potential for sequestration of C in terrestrial ecosysstems, provided that technology is developed to accomplish this in a cost effective and socially acceptable manner and techniques are developed to measure and verify the C being sequestered. Not only do technical barriers have to be overcome, but also environmental, social, and regulatory issues need to be addressed. The balanced portfolio of projects being pursued by DOE under its Carbon Sequestration Program has been selected to address the issues involved and, thus, make a significant contribution to the solution of these problems as rapidly as possible. Soil C sequestration not only restores degraded soils, enhances biomass production, and purifies surface and ground water, but also reduces the rate of $CO_2$ buildup in the atmosphere by offsetting emissions due to fossil fuel combustion. C sequestration (terrestrial and other) is expected to provide about 50% of the reduction in GHG emissions, with efficiency improvements and the use of low-C fuels making up the balance.

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